Polarization switching and induced birefringence in InGaAsP multiple quantum wells at 1.5 mu m

Citation for published version:
Marshall, D, Mazilu, M, Miller, A & Button, CC 2002, 'Polarization switching and induced birefringence in InGaAsP multiple quantum wells at 1.5 mu m', *Journal of Applied Physics*, vol. 91, no. 7, pp. 4090-4094. https://doi.org/10.1063/1.1429794

Digital Object Identifier (DOI):
10.1063/1.1429794

Published In:
Journal of Applied Physics

Journal of Applied Physics

Polarization switching and induced birefringence in InGaAsP multiple quantum wells at 1.5 μm

D. Marshall, M. Mazilu, A. Miller, and C. C. Button

Citation: J. Appl. Phys. **91**, 4090 (2002); doi: 10.1063/1.1429794
View online: http://dx.doi.org/10.1063/1.1429794
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v91/i7
Published by the American Institute of Physics.

Polarization switching and induced birefringence in InGaAsP multiple quantum wells at 1.5 μm

D. Marshall,[a)] M. Mazilu, and A. Miller[b)]
Ultrafast Photonics Collaboration, School of Physics and Astronomy, University of St. Andrews, Fife KY16 9SS, United Kingdom

C. C. Button[c)]
Department of Electronic and Electrical Engineering, EPSRC Central Facility of III-V Semiconductors, University of Sheffield, Sheffield S1 3JD, United Kingdom

(Received 25 September 2001; accepted for publication 30 October 2001)

We analyze the 1.5μm wavelength operation of a room temperature polarization switch based on electron spin dynamics in InGaAsP multiple quantum wells. An unexpected difference in response for left and right circularly polarized pump light in pump–probe measurements was discovered and determined to be caused by an excess carrier induced birefringence. Transient polarization rotation and ellipticity were measured as a function of time delay. © *2002 American Institute of Physics.*
[DOI: 10.1063/1.1429794]

I. INTRODUCTION

Spin-dependent phenomena in semiconductors are attracting increasing interest for all-optical switching in telecommunications systems. Selection rules in quantum wells provide the means of creating excess populations of 100% spin polarized electrons by optical injection. The resulting nonlinear circular dichroism combined with spin relaxation times on the order of a few picoseconds offer possibilities for high bandwidth data routing and switching. The quaternary alloy semiconductor InGaAsP is well established as a primary optoelectronic material system with a range of band gap energy compatible with optical transmission windows in the 1.3 and 1.5 μm spectral regimes. In this article, we have extended our studies[1] of polarization switching in the InGaAsP quantum well system and report a new optically induced birefringence effect.

A number of room temperature all-optical switches based on the spin dynamics of optically created free carriers in multiple quantum wells (MQWs) utilize the effects of carrier spin polarization on linearly polarized light.[2–4] Kawazoe *et al.*[2] utilized the fast hole spin relaxation in type II AlGaAs MQW at wavelengths around 800 nm. Nishikawa *et al.*[3,4] demonstrated a 7 ps switch employing an InGaAs MQW étalon structure with an on/off ratio of 4:1. Hyland *et al.*[1] extended these results to InGaAsP MQWs with room temperature switching times in the range 5–20 ps at 1.52 μm. An alternative approach by Awschalom and Kikkawa,[5] Awschalom and Samarth,[6] and Heberle *et al.*[7] employs spin coherence at low temperatures where femtosecond laser pulses and magnetic fields are used to control the spin and coherent state of excitons.

[a)]Present address: Terahertz Photonics, Rosebank Park, Livingston, EH54 7EJ, UK.
[b)]Author to whom correspondence should be addressed; electronic mail: am8@st-and.ac.uk
[c)]Present address: Marconi, Caswell, Towcester, NN12 8EQ, UK.

II. SPIN RELAXATION AND OPTICAL NONLINEARITIES

Carrier confinement in QWs leads to lifting of the degeneracy of the heavy and light hole valence bands at the Brillouin zone center. Figure 1 shows the optical selection rules for transitions from these states into the conduction band around $k=0$. The right and left polarization states are represented by σ_+ and σ_-, respectively. For excitation with circular polarizations resonant with the heavy hole exciton a single electron spin state is created before the spins randomize. Electron spin relaxation times in QWs have been found to depend strongly on well width and lie within the picosecond range.[8–10] Electron spin relaxation in InGaAsP has been found to be faster than GaAs. This behavior is consistent with the D'yakonov and Perel mechanism.[11] Hole spins decay on subpicosecond times because of ultrafast scattering between the valence bands and the mixed spin nature of the light hole band.

Recent studies of spin relaxation in MQW semiconductors at room temperature have addressed the mechanisms responsible for exciton absorption saturation.[12] While there is 100% spin polarization, subsequent light pulses of the same circular polarization will see an increased transmission due to the exciton saturation effects of phase space filling and screening. Oppositely circularly polarized light, however, will probe an empty spin state so there will be no effects of phase space filling. There will then be a difference in the absorption of the two circular polarization states allowing for a direct measurement of spin relaxation times.

The induced circular dichroism leads to a method of creating an all-optical switch with picosecond recoveries when sufficient carriers partially saturate the exciton absorption. These spin-dependent optical nonlinearities can be both absorptive and refractive.

For linearly polarized light the electric field may be represented by two circular polarization components:

$$E_+ = e^{i\omega t} e^{-\alpha_l z} e^{i n_l k z},$$

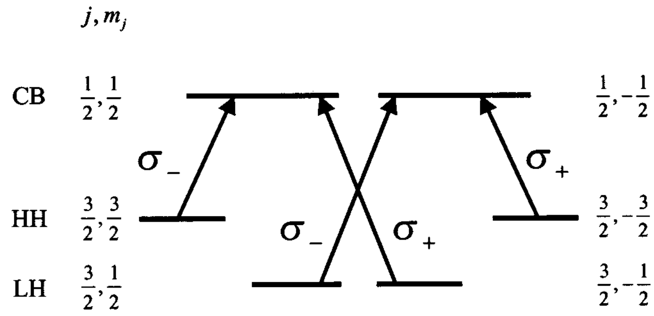

FIG. 1. The selection rules for transitions from the heavy and light holes into the conduction band in the MQWs. The (j,m_j) refer to the quantum numbers for angular momentum and its component along one direction.

$$E_{-}=e^{-i\omega t}e^{-\alpha_r z}e^{-in_r kz},$$

where α_l and α_r are the absorption coefficients and n_l and n_r the refractive indices experienced by the left and right polarizations. The propagation distance through the sample, light frequency, and wave vector are denoted by z, ω, and k, respectively. An excess population of electrons in one of the spin states will create differences between α_l and α_r, and as a causal consequence, n_l and n_r. The index difference will result in a phase difference after propagation through the sample and thus a rotation of the major axis of the linear polarization. The net result of circular polarization dependent nonlinear refraction and absorption will be a rotated elliptical polarization as illustrated in Fig. 2. (The refractive and absorptive differences for the two polarizations have been exaggerated). Therefore, a circularly polarized pump will cause a transient rotation of the polarization and induced ellipticity of a beam as well as a net transmission change while a net spin polarization exists. The induced circular diochroism will recover on the spin relaxation time although full recovery will be determined by the carrier lifetime.

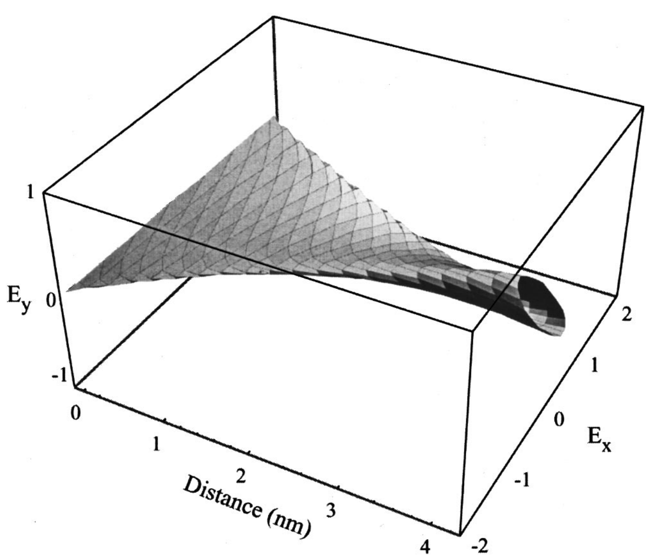

FIG. 2. Theoretical plot of the polarization of probe as a function of distance traveled through the MQWs in the optical switch. The absorption and refractive index changes are large to enable the rotation and ellipticity to be visible.

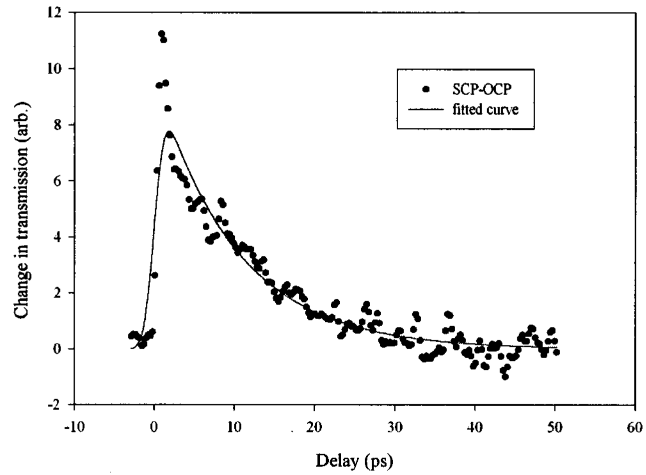

FIG. 3. Difference of the SCP and OCP allowing extraction of the spin relaxation rate.

III. EXPERIMENT

The time resolved experiments were carried out using a PPLN optical parametric oscillator (OPO), producing pulses of 1–2 ps between 1.3 and 1.56 μm.[13] This was synchronously pumped with a self-mode locked Ti–sapphire laser (Spectra Physics Tsunami) tuned to a wavelength of 838 nm, pumped by 5 W of power at a wavelength of 532 nm from a frequency doubled cw diode-pumped Nd:YVO_4 (Spectra Physics Millennia V). The repetition rate of the system was 82 MHz, giving a pulse separation of 12 ns.

The results described here were observed in six doped and undoped MQW samples grown by metalorganic vapor phase epitaxy. This article concentrates on two samples with 60 $In_{0.57}Ga_{0.43}As_{0.93}P_{0.07}$ quantum wells and $In_{0.87}Ga_{0.13}As_{0.29}P_{0.71}$ barriers on an InP substrate. Sample MR1168 had 100 Å thick wells with 70 Å barriers and was undoped. Sample MR850 had 95 Å wells with 75 Å barriers in the intrinsic region of a pin structure. The positions of the heavy hole excitons were at 1.525 and 1.51 μm, respectively.

Spin relaxation times for the six samples were found to be in the 20–36 ps range.[14] For these measurements, the standard pump–probe technique employed circular polarizers in each beam. Figure 3 plots the time evolution of the induced circular dichroism as measured by the difference between configurations with the same circular and opposite circular polarization for pump and probe beams. Fits to the data gave spin relaxation times of 30 ps for MR1168 and 36 ps for MR850.

Unexpectedly long carrier lifetimes were measured in these samples by time resolved photoluminescence.[15] Carrier recombination in the undoped sample, MR1168, was found to be consistent with radiative recombination with a lifetime in excess of 2 μs. Carrier sweepout is important in the doped samples. The recovery time of MR850 was on the order of 40 ns, longer than the repetition time of the OPO used for these polarization-switching studies.

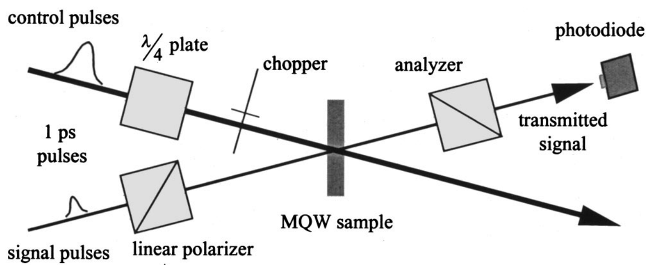

FIG. 4. Experimental setup for the all-optical polarization switch.

IV. OPTICAL POLARIZATION SWITCHING

The induced circular dichroism produced by excitation with circularly polarized light resonant with the heavy hole exciton can be utilized to demonstrate polarization switching devices. The operation of the switch depends on the nonlinear refractive component of the induced circular dichroism associated with exciton absorption saturation in quantum wells.

Linearly polarized *signal* pulses were focused onto the surface of the MQW sample, Fig. 4. A cross-polarized analyzer rejected the transmitted signal to represent the "off" state of the switch. Circularly polarized *control* pulses, focused to overlap the signal beam, created 100% spin polarized electrons by virtue of the selection rules shown in Fig. 1. The presence of the control pulses rotates the linear polarization state of the signal pulses by virtue of the nonlinear refraction, thus creating an "on" state by allowing transmission through the analyzer. The "on" state exists only while a net spin polarization of the electrons exists. This creates an ultrafast polarization switch that decays with the spin relaxation time. The control beam was chopped and the modulation transferred to the signal beam and monitored using a lock-in amplifier.

The time evolution of the switching signal, obtained by monitoring the transmission of the device as a function of the signal pulse delay, is shown in Fig. 5 for sample MR850. Control pulse energies were around 50 pJ and the exponential decay time of the switch is equal to the spin relaxation time of 36 ps. The polarization rotation corresponded to 0.3°/pJ, consistent with previous studies using 100 fs pulses.[1] One attraction of a switch of this type is the large contrast between the on and off states.

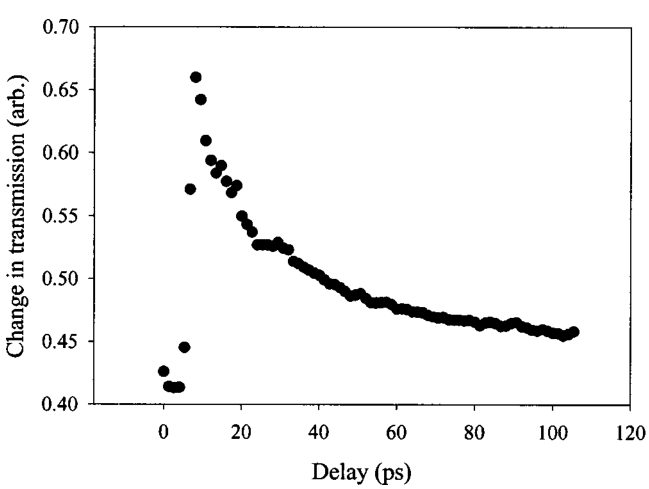

FIG. 5. Change in transmission as a function of delay for the polarization switch, showing a recovery on the order of tens of picoseconds.

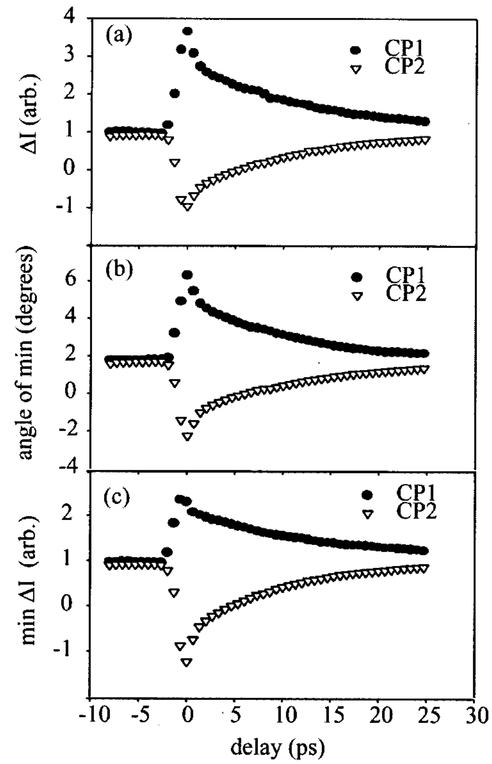

FIG. 6. All-optical polarization switch for the two circular polarizations of the pump: (a) change in transmission as a function of decay, (b) angle of minor axis of ellipse, and (c) absolute value of the minor axis of the ellipse.

V. OPTICALLY INDUCED BIREFRINGENCE

Further studies of the switching configuration revealed a surprising dependence of transmission on the sense of circular polarization rotation of the control pulses. It was found that one orientation of the circular polarization of the pump gave a positive signal and the other a negative signal, Fig. 6(a). For one sense of circular polarization of the pump the switch performed as expected with an increase in signal at zero delay, which then decayed to the original state with the spin relaxation time of 30 ps. The opposite circular polarization of the pump pulse gave a decrease in signal at zero delay, again decaying back to the initial value with the spin relaxation time. The two cases can be thought of as an effective positive and negative switch. Also, note that the signal before zero delay was nonzero. Although the carrier lifetime was established as larger than the pulse separation, the fast spin relaxation time would be expected to lead to a zero signal before zero delay. The results illustrated here are for the undoped sample MR1168 but this phenomenon was observed in both doped and undoped samples. To understand these effects we examined the evolution of the minor axis of the ellipse. A series of pump–probe scans were taken for a range of analyzer angles on either side of the cross polarized position. A cross section of this data in time gives the change in intensity of the probe as a function of analyzer angle at a

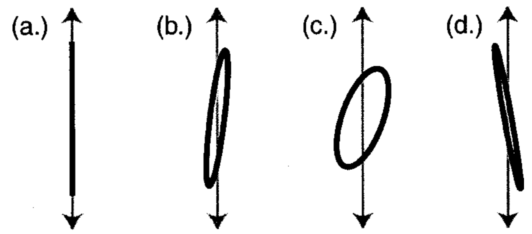

FIG. 7. Schematic representation of the change in polarization of the probe beam (a) before sample, (b) before zero delay (12 ns), (c) after zero delay for one circular polarization of pump (positive switch), and (d) after zero delay for the other circular polarization of the pump (negative switch).

specific delay point. The minimum change in intensity and the angle at which this occurs was obtained by fitting with a $\sec^2$ function. Plotting these two values against delay gives the evolution of the angle of rotation and absolute value of the minor axis, Figs. 6(b) and 6(c), respectively.

Figure 6(b) shows that the two senses of circular polarization of the pump rotate the probe polarization in opposite directions. It is calculated that for this sample, with refractive index $n = 3.2$, a 20 rotation requires a 1.2% difference in the components of circular refractive index, Fig. 2. It is evident from Fig. 6(c) that one circular polarization of the pump increases the ellipticity and the other decreases it. It is also important to observe that there is both a rotation and ellipticity before zero delay. This is summarized schematically in Fig. 7 in order to explain the positive and negative signals. Figure 7(a) gives the initial polarization of the signal beam before the sample. Figure 7(b) shows that there is already some linear polarization rotation and ellipticity imposed on the signal beam after transmission even before zero delay. Figure 7(c) and 7(d) illustrate the changes in polarization for the two senses of circular polarization of the control pulses. Note that in one case both polarization rotation and ellipticity increase, while in the other the polarization and ellipticity decrease. In fact, the polarization rotation can become negative as illustrated in Fig. 7(d). Thus, observing the magnitude of the horizontal components of the polarization in Figs. 7(c) and 7(d) gives consistency with the positive and negative switch results.

Possible explanations for these results are the existence of either a long-lived circular dichroism or a long-lived birefringence in the sample. Circular dichroism would arise from optical activity of a long-lived component of spin relaxation. No long-lived spin relaxation component has been evident in the spin relaxation experiments. InGaAsP is a cubic zincblende III–V semiconductor with no inbuilt helical structure that would lead to optical activity. By carrying out a series of experiments whereby the sample was reversed then rotated, and the control and signal beams interchanged then the angle between them altered, the possibility of optical activity was eliminated. The conclusion was that birefringence rather than an optical activity caused the effects illustrated in Fig. 7.

A cubic structure cannot exhibit birefringence. A quantum well structure can be birefringent for propagation in the plane of the wells, but is not expected in our geometry. However, the InGaAsP quantum wells were grown on a very

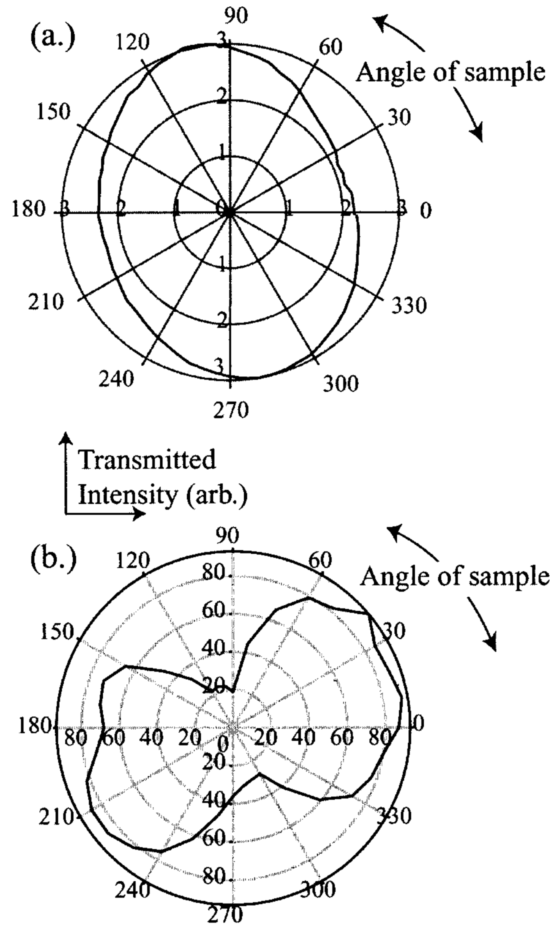

FIG. 8. (a) Transmission of a linear polarized beam through the sample and an analyzer crosspolarized with the initial beam as a function of the angle of sample MR1168. (b) Transmitted signal of switch before zero delay as a function of the angle.

small wedge (0.03°). It is thus possible that this break in symmetry introduces a small degree of birefringence into the sample when excess carriers are present. Therefore, an experimental investigation of the rotational effects of the sample was performed. The birefringence was examined in a single beam experiment. A linearly polarized train of pulses was passed through the sample and an analyzer crosspolarized with the initial beam. The transmitted signal was measured as the sample was rotated about an axis perpendicular to the surface, Fig. 8(a). A very distinct change in signal was observed as the analyzer was rotated. This indicated that this beam created a small long-lived birefringence. The long carrier lifetime ensured carrier buildup pulse-to-pulse to enhance the effect.

The effect of excited carriers on the birefringence was also measured by rotating the sample in the two-beam switch configuration. This was performed at a constant time just before zero delay i.e., 12 ns after the previous control pulse. The signal experienced a significant change as the sample was rotated [Fig. 8(b)], confirming a carrier induced birefringence. The induced birefringence itself could be employed as a polarization switching mechanism, however the recovery is slow because of the long-lived carriers in this case. The phenomenon could find applications in optical switches if the effect could be combined with shorter carrier lifetimes.

VI. CONCLUSIONS

Fast spin relaxation and sensitive excitonic optical nonlinearities in InGaAsP MQWs promise useful polarization switching applications. The picosecond time scales on which these operate allow for the development of ultrafast devices. An all-optical switch with two states dependent on the sense of circular polarization of the control pulse has been explained in terms of the existence of an induced birefringence in the InGaAsP wells.

ACKNOWLEDGMENTS

This work was supported by EPSRC (Grant Nos. GR/L87125 and GR/N14040/01). D.M. wishes to thank EPSRC for her studentship.

[1] J. T. Hyland, G. T. Kennedy, A. Miller, and C. C. Button, IEEE Photonics Technol. Lett. **10**, 1419 (1998).
[2] T. Kawazoe, Y. Masumoto, and T. Mishina, Phys. Rev. B **47**, 10452 (1993).
[3] Y. Nishikawa, A. Tackeuchi, M. Yamaguchi, S. Muto, and O. Wada, IEEE J. Sel. Top. Quantum Electron. **2**, 661 (1996).
[4] Y. Nishikawa, A. Tackeuchi, S. Nakamura, S. Muto, and N. Yokoyama, Appl. Phys. Lett. **66**, 839 (1995).
[5] D. D. Awschalom and J. M. Kikkawa, Phys. Today **52**, 33 (1999).
[6] D. D. Awschalom and N. Samarth, Solid State Commun. **107**, 663 (1998).
[7] A. P. Heberle, J. J. Baumberg, E. Binder, T. Kuhn, K. Kohler, and K. H. Ploog, IEEE J. Sel. Top. Quantum Electron. **2**, 769 (1996).
[8] T. C. Damen, L. Vina, J. E. Cunningham, J. Shah, and L. J. Sham, Phys. Rev. Lett. **67**, 3432 (1991).
[9] A. Tackeuchi, T. Kuroda, S. Muto, and O. Wada, Physica B **272**, 318 (1999).
[10] R. S. Britton, T. Grevatt, A. Malinowski, R. T. Harley, P. Perozzo, A. R. Cameron, and A. Miller, Appl. Phys. Lett. **73**, 2140 (1998).
[11] M. I. D'Yakonov and V. I. Perel, Sov. Phys. JETP **33**, 1053 (1971).
[12] A. Miller, P. Riblet, M. Mazilu, S. White, T. M. Holden, A. R. Cameron, and P. Perozzo, J. Appl. Phys. **86**, 3734 (1999).
[13] D. T. Reid, G. T. Kennedy, A. Miller, W. Sibbett, and M. Ebrahimzadeh, IEEE J. Sel. Top. Quantum Electron. **4**, 238 (1998).
[14] D. Marshall and A. Miller (unpublished).
[15] J. M. Smith, G. S. Buller, D. Marshall, A. Miller, and C. C. Button, Appl. Phys. Lett. (accepted).